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I_c DEGRADATION DUE TO CABLING IN INTERNAL TIN Nb_3Sn

Emanuela Barzi

Abstract:

Samples of IGC Nb_3Sn virgin strand, and of strand extracted from cables having different packing factors were heat treated in argon in an IB3's tube furnace and tested at the SSTF of the TD. The I_c dependence on field at 4.2K was measured for virgin and for extracted strands, and the I_c degradation due to cabling was calculated as a function of the packing factor and of field.

1. INTRODUCTION

In June '98, IGC delivered to Fermilab 20.72kg (*i.e.* 2,813m) of 1mm, 61SE, 39.5% Cu, Low Tin Nb_3Sn multifilamentary strand (billet No. FR20444) divided in four spools of 795m (piece No.1), 799m (piece No.2), 823m (piece No.3), and 396m (piece No.4-1).

From each spool, parts of the strand were sent to LBNL for cabling. Four Rutherford cables 39.6m, 16m, 6m, and 7.6m long were made with packing factors of 91.6%, 93%, 91%, and 90% respectively. Four samples of virgin strand, and four strands extracted from each cable (see Figure 1) were wound on grooved cylindrical barrels made of a Ti-6Al-4V alloy, and fixed on two removable Ti-alloy end rings, as shown in Figure 2. Twelve hairpin samples were also assembled, four out of virgin strands, four out of cable-extracted strands with their thin edge (lower edge in Figure 1) supported on the central straight section of stainless steel holders, and four out of cable-extracted strands but with their thick edge (upper edge in Figure 1) on the holder. This is also shown in Figure 2. This set of 20 samples was heat treated in argon at various temperatures for a total time of about 600hr to form superconducting Nb_3Sn. The exact heat treatment schedule is specified in Appendix A.

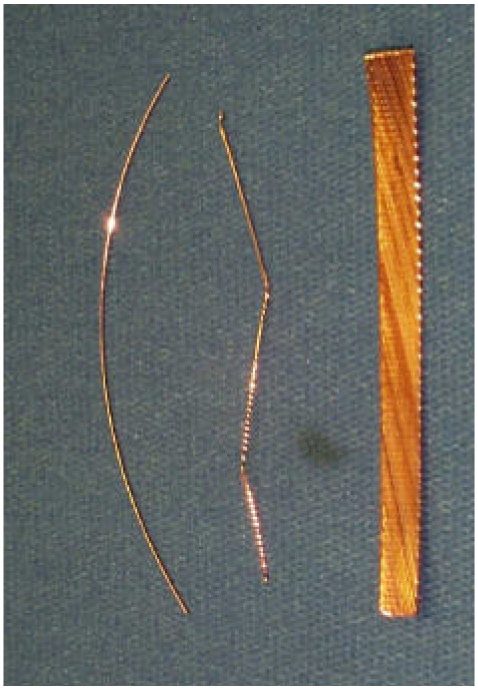

Fig. 1: Examples of virgin strand, of cable-extracted strand (upper edge is thick, lower edge is thin), and of a piece of cable.

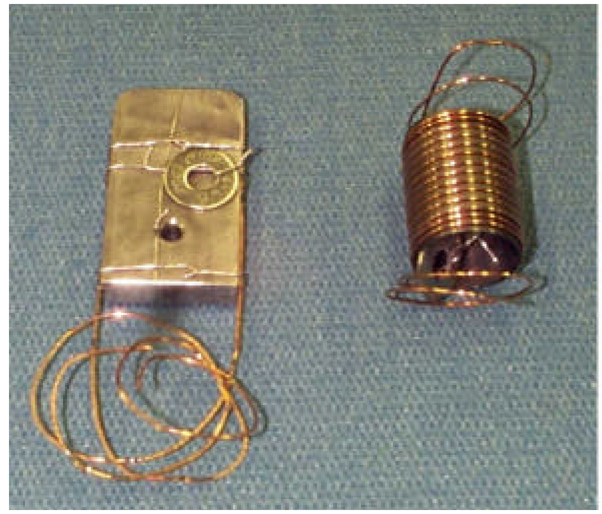

Fig. 2: Stainless steel holder with a hairpin sample (on the left), and a Ti-6Al-4V barrel with a coil sample, ready for reaction.

After the reaction phase, the Ti-alloy end rings of the cylindrical barrels were replaced by copper rings, and the I_c of a majority of the coil samples was measured at 4.2K and various fields. Results are presented on the virgin sample from spool No.2, and on the cable-extracted samples with packing factors of 93%, 91%, and 90%.*

2. CABLE GEOMETRY

The geometry of a keystoned Rutherford cable (not to scale) looks as follows:

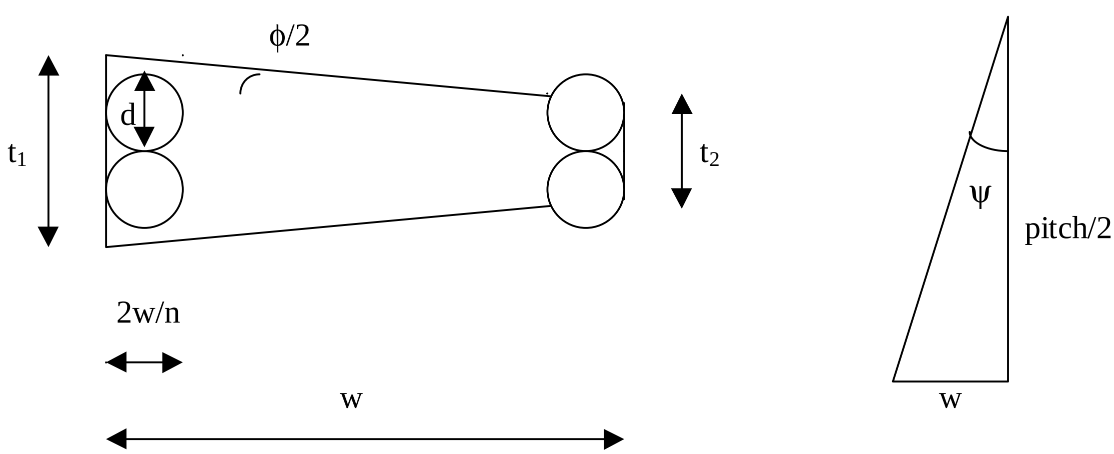

Fig. 3: Geometry of a keystoned Rutherford cable.

* The cable-extracted sample with a packing factor of 91.6% broke on a thick edge during heat treatment.

where n is the number of strands in the cable, w is the cable width, t_1 is the major edge thickness, t_2 is the minor edge thickness, ϕ is the keystone angle, and ψ is the lay angle.

The packing factor, P, of a cable is defined as the ratio of the cross section area occupied by the strands to the overall cross section of the cable. In formulae:

$$P = \frac{n\pi d^2}{2w(t_1 + t_2)\cos\psi} \qquad (1)$$

The four cables made at LBNL had w = 14.233mm, ϕ = 1.021°, ψ = 14.53°. The different packing factors were obtained by varying the average thickness, which was 1.8161mm, 1.7965mm, 1.7852mm, and 1.7579mm, corresponding to packing factors of 90%, 91%, 91.6%, and 93% respectively.

3. I_c MEASUREMENTS

The I_c was measured with the 10^{-14} Ω·m resistivity criterion at 4.2K between 10T and 15T. The results for the virgin and extracted strands in the coil configuration are shown in Figure 4 and Table 1.

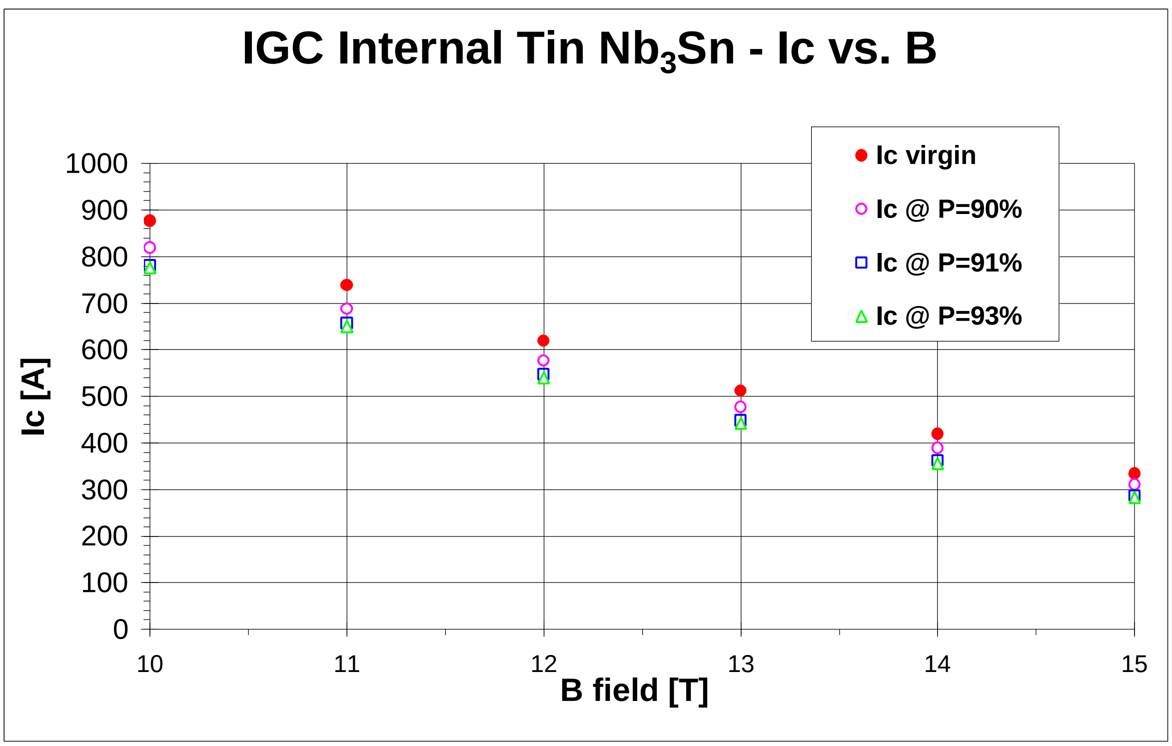

Fig. 4: I_c dependence on field between 4T and 15T at 4.2K of the virgin and extracted strands in the coil configuration.

B field [T]	Ic (ρ_c) virgin [A]	Ic (ρ_c) P=90% [A]	Ic (ρ_c) P=91% [A]	Ic (ρ_c) P=93% [A]
10	877	819	781	776
11	739	688	657	650
12	619	577	547	540
13	512	477	448	442
14	419	389	362	356
15	334	311	287	283

Table 1: Critical currents of the virgin and extracted strands measured with the $10^{-14}\ \Omega\cdot$m resistivity criterion at 4.2K between 10T and 15T.

The I_c degradation, expressed as the ratio of the cable-extracted strand's I_c to the I_c of the virgin strand, is plotted as a function of field for the three different packing factors in Figure 5.

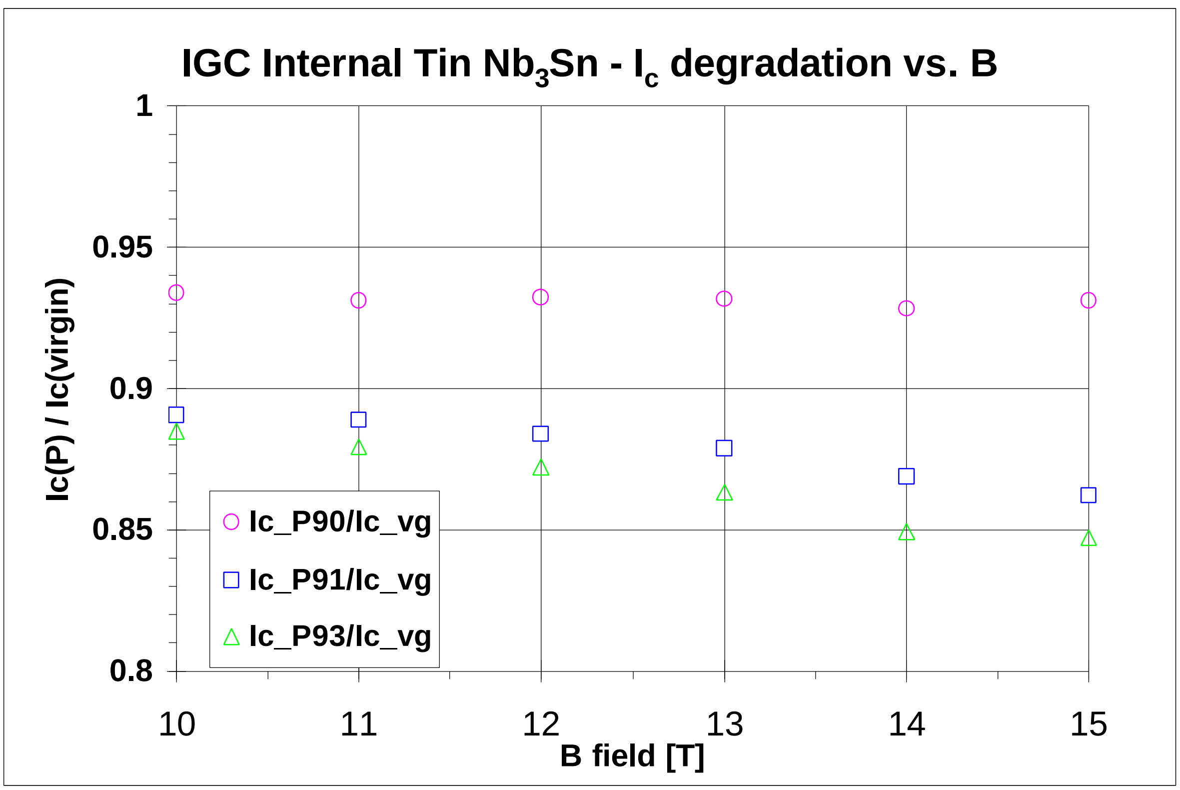

Fig. 5: Ratios of the cable-extracted strands' I_c to the I_c of the virgin strand as a function of field for three different packing factors.

In Figure 6, the I_c degradation is shown as a function of the packing factor at a field of 12T. The value of zero degradation, *i.e.* a ratio of the cable-extracted strand's I_c to the I_c of the virgin strand of 1, for a packing factor of 0.785, has been added to this plot as a reference value (*i.e.* $\pi/4$ for an undeformed round strand inscribed in a square).

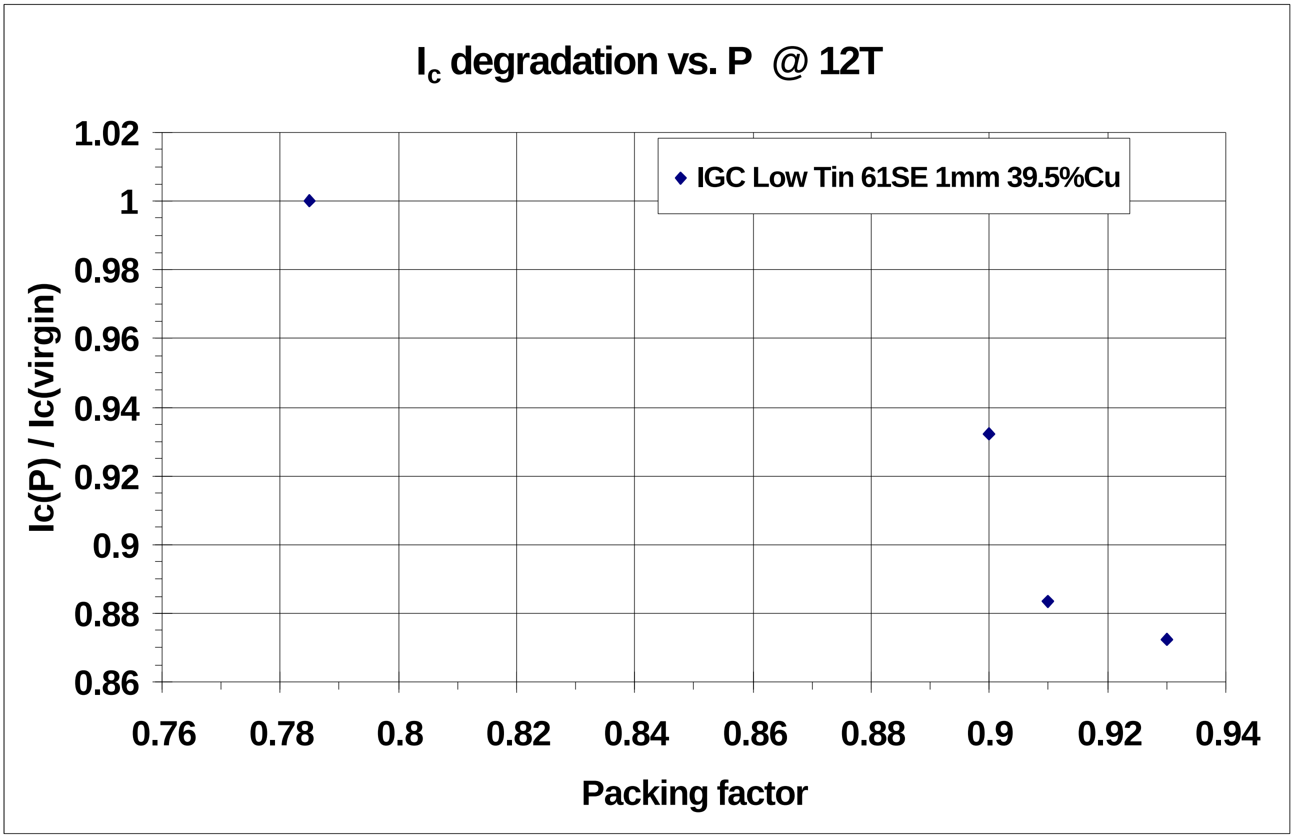

Fig. 6: I_c degradation as a function of the packing factor at a field of 12T.

4. I_c MEASUREMENTS ON SINGLE EDGES

Equation (1) gives the average packing factor of the whole cable. Nevertheless, as can be understood from Figure 3, the strands on the minor edge side are more compacted together than those on the major edge side. An equivalent packing factor can be inferred for the layer of strands on either side as follows:

$$P(thick\,edge) = \frac{\pi d^2/4}{\frac{2w}{n}\cdot\frac{t_1}{2}\cdot\cos\psi} \qquad (2)$$

$$P(thin\,edge) = \frac{\pi d^2/4}{\frac{2w}{n}\cdot\frac{t_2}{2}\cdot\cos\psi} \qquad (3)$$

For example, the cable with a 91% packing factor and an average thickness of 1.7965mm, therefore with a major edge thickness t_1 of 1.9233mm, and a minor edge thickness t_2 of 1.6697mm, has P(thick edge) ≈ 85%, and P(thin edge) ≈ 98%.

By placing a pair of voltage taps on a cable-extracted strand on each side of an edge, and taking care of minimizing the noise, it is possible to measure the local I_c degradation. This was done at 4.2K between 10T and 15T on the thick edge of the cable-extracted sample with a 91% packing factor. The voltage taps were placed 6cm away from each other. The results are shown in Figure 7, where the local

I_c measurements have an increased error with respect to the average I_c measurements carried on the whole sample. This additional error is related to the larger relative noise amplitude [1].

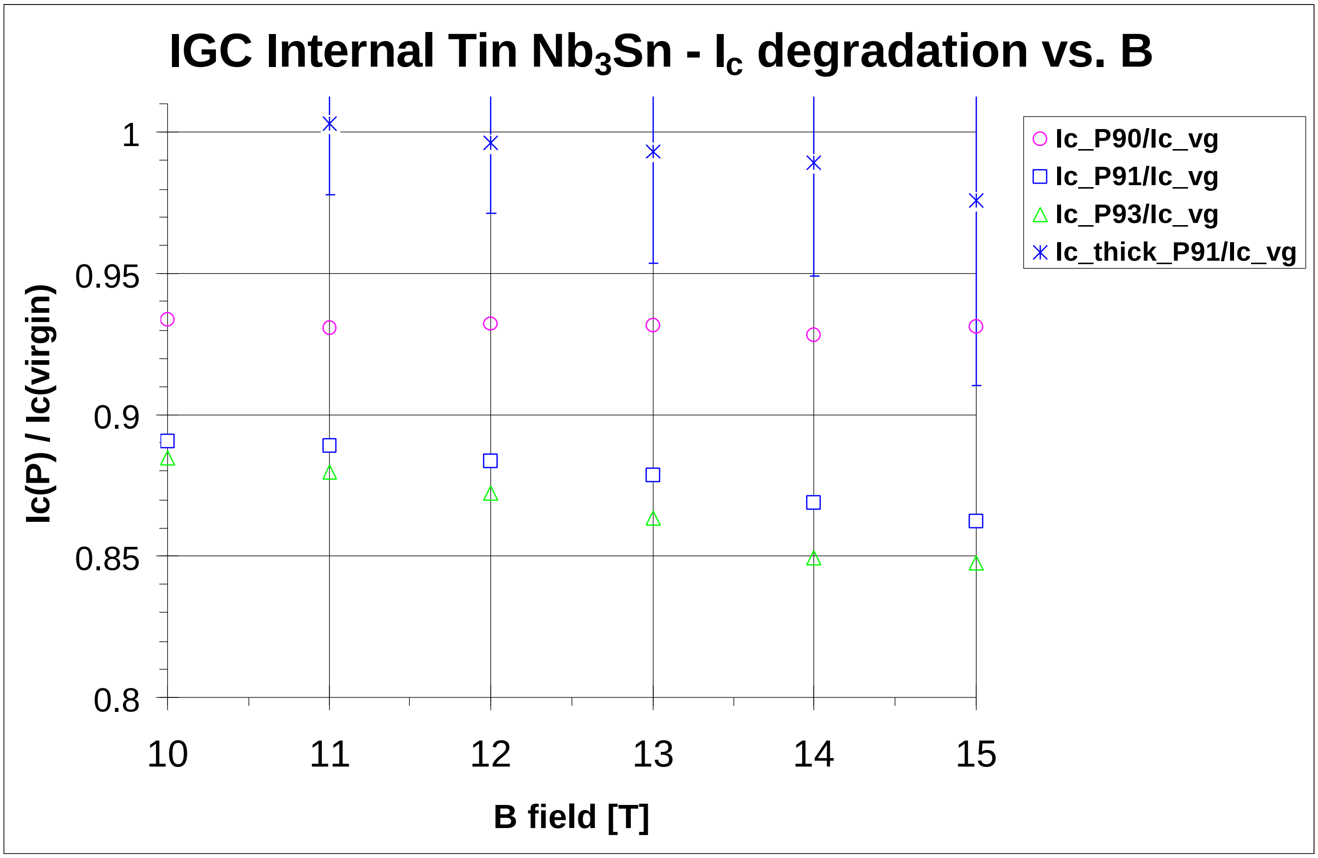

Fig. 7: Ratios of the local I_c on the thick edge of the cable-extracted strand with 91% packing factor to the I_c of the virgin strand as a function of field. The error bars represent the increased error of local I_c measurements with respect to the average I_c measurements carried on the whole sample. This additional error is related to the larger relative noise amplitude

Figure 8, where the I_c degradation is shown as a function of all tested packing factors at a field of 12T, represents a summary of these studies.

5. CONCLUSIONS

In IGC internal tin Nb_3Sn (low tin), I_c degradation due to cabling appears to be small. Below a 90% cable's packing factor, the I_c degradation is less than 8% up to 15T.

Studies on I_c degradation will continue on more IGC superconductor –low tin and intermediate tin– and on jelly roll Nb_3Sn.

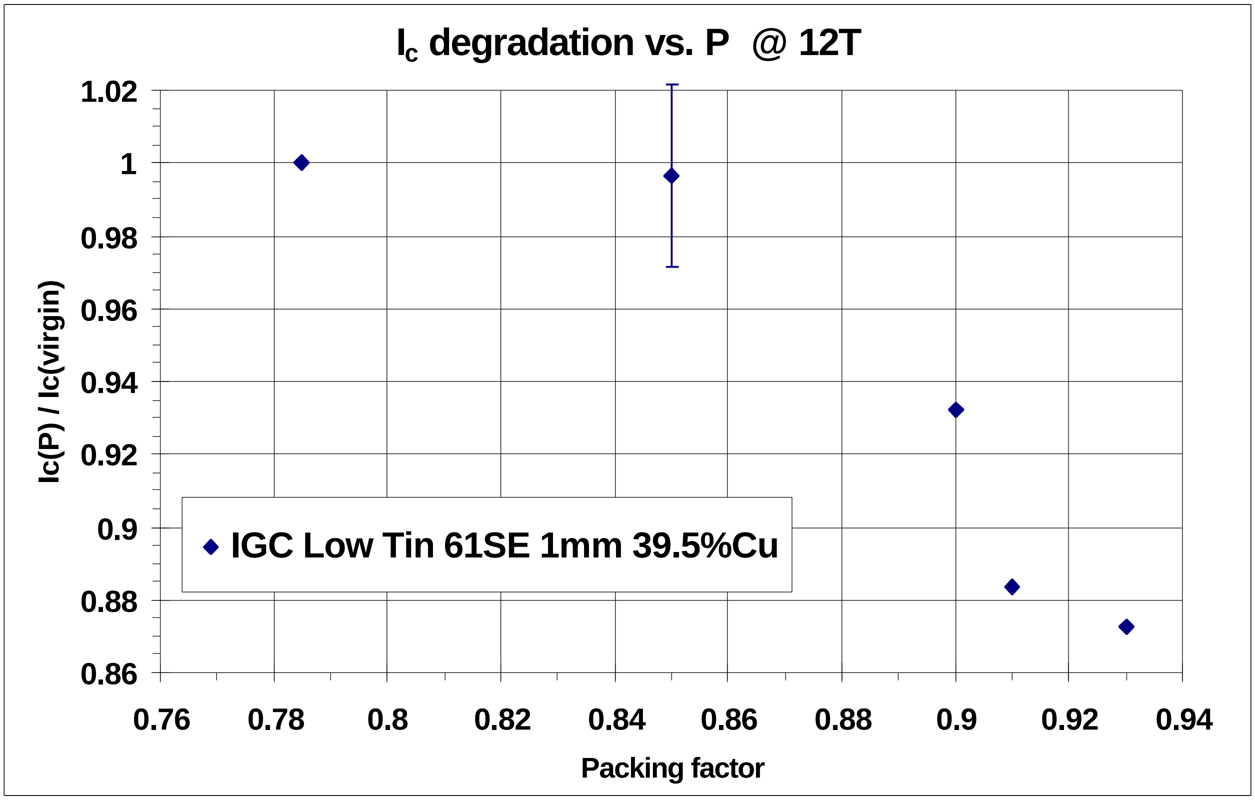

Fig. 8: I_c degradation as a function of all tested packing factors at a field of 12T.

APPENDIX A

HT	T [°C]	R [°C/h]	t [h]	T [°C]	R [°C/h]	t [h]	T [°C]	R [°C/h]	t [h]	T [°C]	R [°C/h]	t [h]	Total t [h]
IGC	185	6	48	460	6	100	570	25	200	650	25	175	604

REFERENCES

[1] E. Barzi, *Error analysis of short sample J_c measurements at the Short Sample Test Facility*, TD-98-055.